A 400-km-long piggyback basin (Upper Aptian–Lower Cenomanian) in the Eastern Alps

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ABSTRACT

The Late Aptian to Early Cenomanian Tannheim–Losenstein basin constitutes an early, deep-marine piggyback trough which formed on the Cretaceous orogenic wedge of the Eastern Alps. The narrow basin extended over more than 400 km from the western part of the Northern Calcareous Alps into the Western Carpathians (Slovakia), as suggested by similarities in stratigraphy – e.g. the common coarsening upward succession of marls, sandstones, and conglomerates – and by similarities in timing of deformation and the uniform composition, e.g. similar heavy mineral assemblages. The coarsening-upward succession resulted from the progradation of a coarse-grained slope apron into a hemipelagic basin. The composition of detrital material constitutes evidence for a uniform source area to the north, along the entire length of the basin, comprising continental basement, Mesozoic sediments and remnants of ophiolites. The basin formation marked the onset of compression along the northern Austroalpine plate boundary.

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Introduction

Piggyback basins (Ori and Friend, 1984) comprise sedimentary basins that formed on active thrust sheets. Based on basin geometry and depositional systems, two end-member types of piggyback or thrust-top basins have been distinguished. Type 1 basins are deep-water basins that occur mainly as elongated, synsedimentary deforming troughs in the footwall of thrusts in the early stages of orogenic wedge development and underfilled foreland basins (e.g. Ori and Friend, 1984; Lash, 1990). Type 2 piggyback basins are terrestrial to shallow marine 'intramontane' basins that are formed predominantly during late orogenic stages (e.g. Ori and Friend, 1984; Nijman, 1998).

This paper describes the geometry and evolution of an early, deep-marine piggyback trough that formed on the Cretaceous orogenic wedge of the Eastern Alps and the Western Carpathians. The narrow basin extended over a considerable horizontal distance as suggested by similarities in stratigraphy and the timing of deformation. The basin characterized a significant stage in the Cretaceous evolution of the Austroalpine northern boundary.

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Geological setting

The Eastern Alps are the result of polyphase orogeny, controlled by repeated convergence of the African upper plate relative to the European lower plate (e.g. Dewey *et al*., 1989; Wortmann *et al*., 2001). During the Cretaceous, the ultimate closure and suturing of the Triassic Tethyan ocean (Gawlick *et al*., 1999; Faupl and Wagreich, 2000) and the beginning of oblique southward subduction of the Penninic ocean below the Austroalpine active margin (e.g. Frisch, 1979; Wagreich, 1995) caused deformation and north-westward thrusting (e.g. Linzer *et al*., 1995), forming the early thrust stack of the Northern Calcareous Alps (NCA). Oblique subduction of the Penninic ocean including parts of the Rhenodanubian Flysch Zone (Fig. 1) resulted in a strong dextral shearing component influencing thrusting and basin formation in the NCA (e.g. May and Eisbacher, 1999). A minimum NW–SE shortening of the NCA of more than 60% was estimated by Linzer *et al*. (1995).

During Early Cretaceous thrusting, widespread deposition of pelagic limestones in the northern part of the NCA was replaced by (silici)clastics filling basins formed in front and on top of moving thrust sheets (e.g. Gaupp, 1983; May and Eisbacher, 1999). These syntectonic strata comprise several formations (Fig. 1), including Albian to Cenomanian sandstones and conglomerates of the Losenstein Formation (Kollmann, 1968) in the northern NCA and their continuation into the Western Carpathians (e.g. Faupl *et al*., 1997). Subsequent polyphase Tertiary tectonics (e.g. Decker and Peresson, 1996) strongly deformed the Cretaceous continental margin and the sedimentary basin fills, and largely destroyed the geometry of these basins.

The Tannheim–Losenstein basin

Deposits of the Tannheim–Losenstein basin are confined to faulted and partly overturned, narrow synclines within the Allgäu–Ternberg–Frankenfels nappe system, the structurally deepest, northernmost thrust sheets of the NCA (Figs 1 and 2). The sedimentary evolution of the Tannheim–Losenstein basin is represented by two sections (Fig. 1), one from the eastern NCA (Losenstein type section, Kollmann, 1968; Wagreich and Sachsenhofer, 1999; Wagreich, in press), and the other from the Allgäu in the western NCA (composite section Hindelang–Krähenwand–Kleebach: Gaupp, 1982; von Eynatten, 1996). Data from the Central Western Carpathians (CWC) of the Slovak Republic (Križna Nappe Fatricum of the Male Karpaty and Klape Unit of the Pieniny Klippen Belt; e.g. Misík *et al*., 1981; Plašienka, 1995) have been

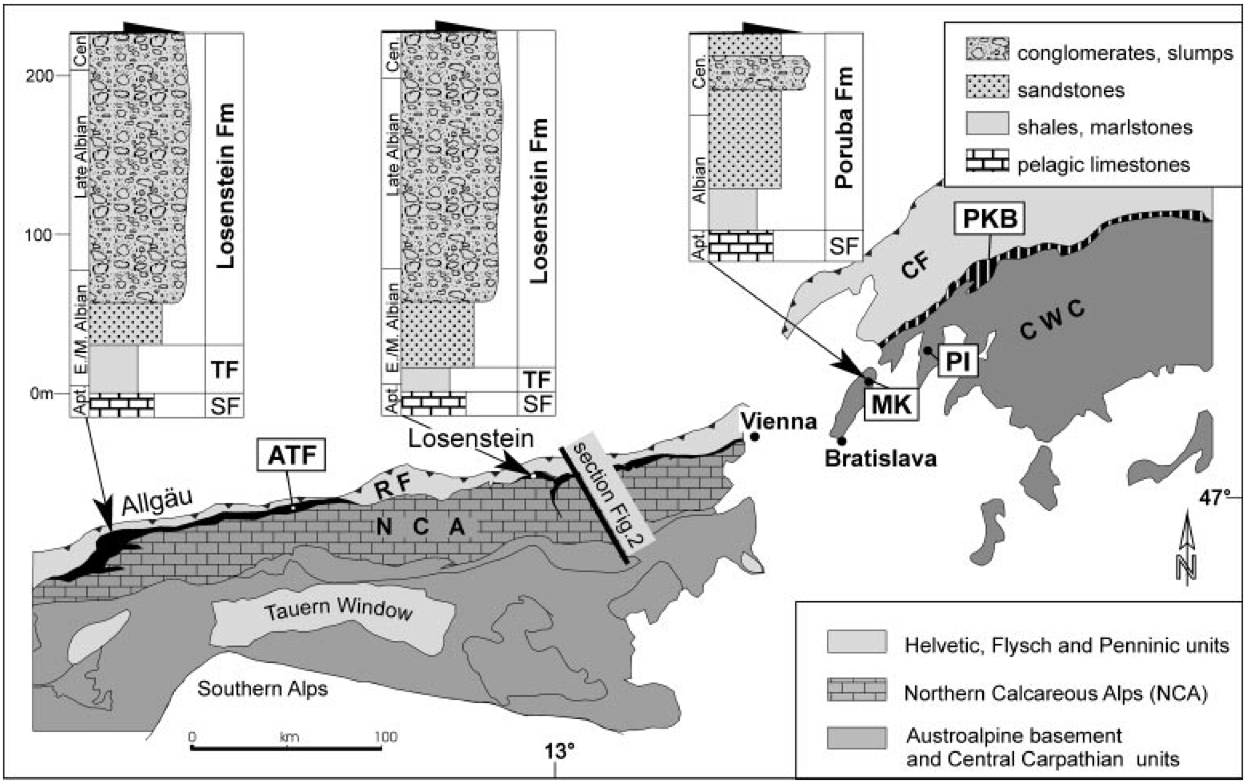

Fig. 1 Simplified geological map of the Eastern Alps and the Western Carpathians. Geological sections display Albian–Cenomanian successions of the Northern Calcareous Alps (a part of the Austroalpine nappe stack) and the Central Western Carpathians. ATF, Allgäu–Ternberg–Frankenfels nappe system; NCA, Northern Calcareous Alps; SF, Schrambach Formation; TF, Tannheim Formation; RF, Rhenodanubian Flysch Units; CF, Carpathian Flysch Units; PKB, Pieniny Klippen Belt; CWC, Central Western Carpathians; MK, Malé Karpaty Mountains; PI, Považský Inovec Mountains.

included to demonstrate the continuity of the basin to the east.

The Tannheim–Losenstein basin formed in front of NW-thrusting, structurally higher NCA nappes, i.e. the Lechtal–Reichraming–Lunz nappe system and Tirolic and Juvavic nappes (Fig. 2). Sedimentation within the basin ended by overthrusting of these southern units, stratigraphically constrained by the youngest, Lower Cenomanian sediments found within the nappe (Weidich, 1990).

Sedimentology of the basin fill

In the northern part of the NCA, Lower Cretaceous limestones and marl–limestone beds of the Schrambach Formation are overlain by 10–30-m-thick marlstones and calcareous shales of the Upper Aptian to Middle Albian Tannheim Formation (Wagreich and Sachsenhofer, 1999). Bathyal foraminiferal assemblages of the marlstones and shales point to sedimentation within a deep-water basin with fine-grained siliciclastic input (Weidich, 1990). Lower Albian black shales occur both in the western and in the eastern NCA, as a consequence of global anoxia (OAE 1b, Wagreich and Sachsenhofer, 1999), which implies open seaways in the western Tethys and the Atlantic Ocean.

This shaly interval is followed by the 100–350-m-thick coarsening-upward succession (Fig. 1) of the Losenstein Formation (Middle/Upper Albian–lowermost Cenomanian; Weidich, 1990), comprising turbidites, deep-water conglomerates and slump horizons. In the CWC, contemporaneous siliciclastic deposits are grouped into the Poruba Formation (Misík *et al.*, 1981; Faupl *et al.*, 1997). The continuous section in the type area of the Losenstein Fm., the Stiedelsbach near Losenstein, starts with thin sandy turbidites and laminated siltstone-shale intervals (see Wagreich, in press, for detailed sedimentological descriptions). Sandstone beds show complete or incomplete Bouma cycles. The amount of massive sandstone beds, conglomerates, pebbly mudstones and slump intervals increases upsection. Normal and inversely graded clast-supported conglomerates and matrix-supported pebbly mudstones are found in 5–15-m-thick intervals, without distinct grain-size trends from interbedded thin-bedded sandstones. Slump intervals display folded siltstone–shale beds with rare sandstone layers. The youngest preserved part in the section is dominated by thick slump beds (> 9 m) and matrix-supported conglomerates including limestone blocks up to 1.2 m in diameter.

The bathyal microfauna and the close association of slumps together with coarse, channelized conglomerates, fine-grained thin-bedded sandy turbidites, and debris flow deposits indicate a deep-water slope environment of deposition. The noncyclic facies arrangement and the distribu-

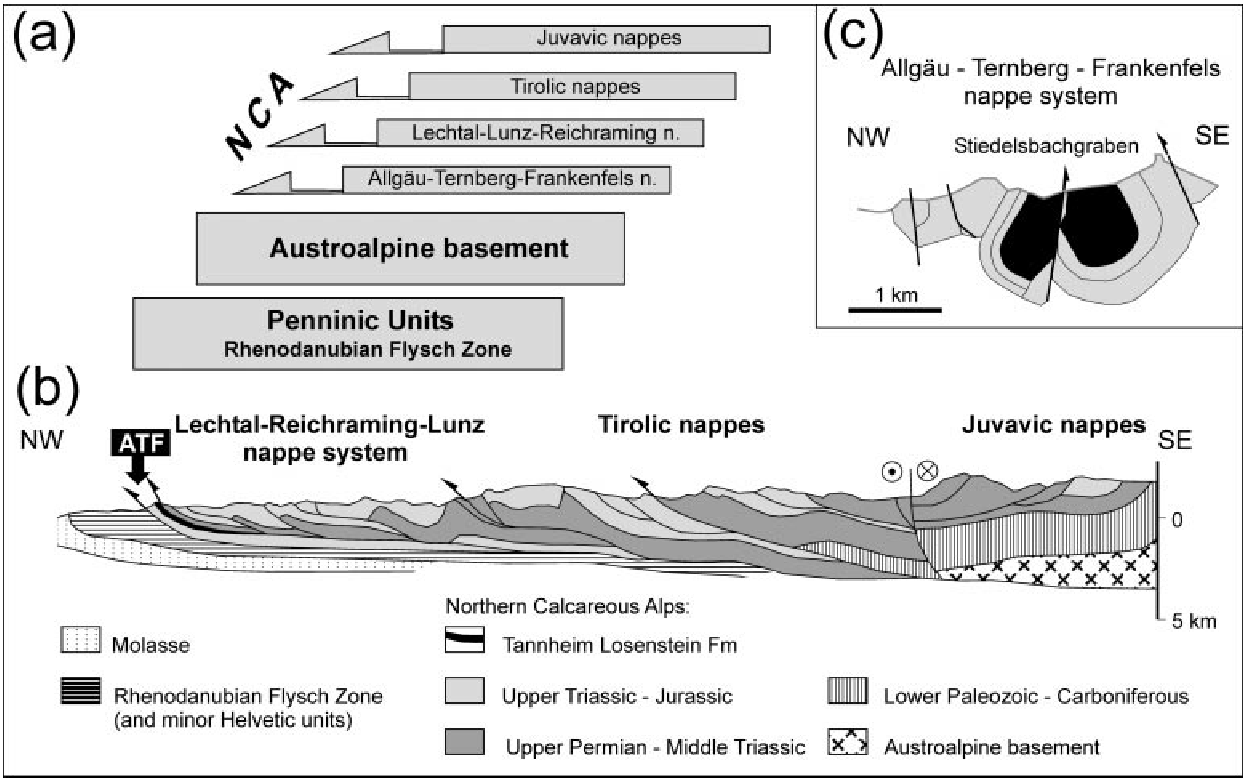

Fig. 2 (a) Tectonic framework of the Northern Calcareous Alps. (b) Cross-section for the eastern part of the Northern Calcareous Alps, modified from Linzer *et al.* (1995); ATF, Allgäu–Ternberg–Frankenfels nappe system. (c) Section through the Losenstein synform in the type area of the Losenstein Formation, based on Egger (1988).

tion of channels and slumps implies a linear clastic wedge, i.e. a slope apron in the sense of Pickering *et al.* (1989). This coarse-grained slope apron, including small channels and debris flow tongues, was fed from a continuous source with multiple feeders. The coarsening-upward succession with abundant slumps in the upper part may be interpreted as progradation of the slope apron into a pelagic basin. Coarse-grained slope aprons typically form across an active synsedimentary fault margin characterized by high relief and ongoing deformation (Reading and Richards, 1994; Stow and Mayall, 2000).

Basin geometry

Reconstructions of the geometry of the Tannheim–Losenstein piggyback basin in the Losenstein area based on balanced cross-sections (Linzer *et al.*, 1995) result in a minimum basin width of about 15 km. Taking into account strongly deformed northernmost tectonic outliers of the eastern NCA (Egger, 1988), a minimum width of 25 km is suggested. The shallow-water to subaerial part of the northern basin margin, which must have existed according to reported southward palaeotransport directions (Gaupp, 1982), is now completely missing. Therefore, a minimum width of about 10 km must be added to the reconstructed basin width, as the coarse slope apron facies argues for a small, relatively steep shelf. To the south, Aptian–Albian shallow-water sandy limestones with crinoidal debris and mollusc fragments along the northern margin of the Lunz thrust indicate the southern margin of the Tannheim–Losenstein basin in front of the Lechtal–Reichraming–Lunz nappe system. Further to the south, no Albian deposits are known in the eastern NCA, whereas in the westernmost NCA, the synorogenic Kreideschiefer basin formed contemporaneously (May and Eisbacher, 1999).

The E–W extent of the basin can be reconstructed from the presence of the Losenstein Formation along the entire length of the Allgäu–Ternberg–Frankenfels thrust system, from the western Allgäu (Gaupp, 1982) to the eastern margin of the NCA near Vienna (Löcsei, 1974). This adds up to a minimum length of about 300 km. Similar successions in the Western Carpathians suggest that the basin extended further to the east.

Composition of detrital material

Sandstones and conglomerates of the Losenstein Formation show a remarkably uniform composition along the entire length of the basin. Framework grain compositions of sandstones indicate litharenites of recycled orogen derivation (Fig. 3a; Gaupp, 1980, 1982; von Eynatten, 1996; von Eynatten and Gaupp, 1999). Heavy mineral analysis shows significant amounts of chrome spinel in both the eastern and western NCA (Fig. 3b; Gaupp, 1982; Pober and Faupl, 1988; von Eynatten and Gaupp, 1999). Sandstones of the eastern NCA display high amounts of chrome spinel (mean 20%), zircon and

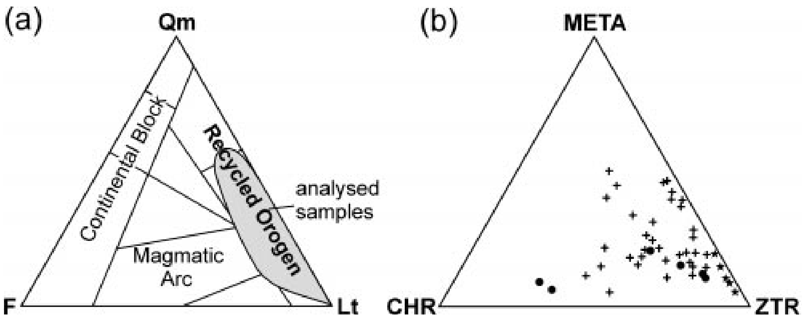

Fig. 3 (a) Modal analysis of sandstones of the Losenstein Formation (data from von Eynatten and Gaupp, 1999; Wagreich, unpubl.) and the Poruba Formation (Wagreich, unpubl.) within the QmFL provenance diagram of Dickinson (1985). Samples fall into the (lithic) recycled orogen field. (b) Ternary plot of samples from the Losenstein Formation, the Poruba Formation and Albian sandstones of the Klape unit of the Western Carpathians. CHR, chrome spinel; META, garnet, staurolite, chloritoid, epidote, green and blue sodic amphiboles; ZTR, zircon, tourmaline, rutile; crosses, Losenstein Formation of the eastern NCA; circles, Losenstein Formation of the western NCA; stars, Poruba Formation of the CWC.

tourmaline, plus strongly varying amounts of chloritoid (up to 46%) and apatite (Wagreich, in press). Sodic amphiboles – mainly glaucophane and ferro-glaucophane – occur both in the western and in the eastern NCA (up to 17%), and indicate HP rocks in the source area (von Eynatten *et al*., 1996; Winkler *et al*., 1997).

Compositions of sandstones from the CWC are similar, including heavy mineral assemblages rich in chrome spinel and significant amounts of blue sodic amphiboles (Wagreich, in press), which display similar chemical compositions to those from the NCA (Ivan and Sýkora, 1993). Coeval coarse deposits of the Klape unit in the Pieniny Klippen Belt (Fig. 1) also contain pebbles of metabasalts with blueschist facies imprint and sodic amphiboles of late Jurassic age (Dal Piaz *et al*., 1995).

Clast compositions of conglomerates are dominated by 'exotic' rock types unknown in the successions of the NCA, such as quartz porphyries, andesitic volcanics, pebbly quartzites, metasandstones, Jurassic and Lower Cretaceous neritic limestones of Urgonian type (Löcsei, 1974; Gaupp, 1983; Schlagintweit, 1991). Clast compositions show only minor variations from the western to the eastern NCA, and similar pebble types have been reported from the CWC (Misík *et al*., 1981).

Palaeocurrent data from flute casts and conglomeratic channels imply a northern provenance for the siliciclastics both in the western and eastern NCA (Gaupp, 1983; Wagreich, in press) and in the Western Carpathians (Misík *et al*., 1981). Palaeomagnetic data indicate only minor rotations of about 30° counter-clockwise since the Cretaceous (Haubold *et al*., 1999). The similar compositions of the detrital material thus suggest a uniform source area along the entire northern basin margin, comprising non-NCA 'exotic' material, such as metamorphic basement slices, granites, quartz porphyries and rare intermediate-to-basic volcanics, as well as exotic Mesozoic sedimentary rocks (Gaupp, 1983; von Eynatten, 1996). Chrome spinel and rare serpentinitic grains indicate also the presence of ultrabasic bodies in the source area (Pober and Faupl, 1988; von Eynatten, 1996).

Discussion

The Tannheim–Losenstein basin displays characteristics of a typical type 1 deep-water piggyback basin, formed by syntectonic subsidence in the footwall of thrusts. Such basins are common in the initial phases of thrusting within orogenic wedges or in early, underfilled stages of foreland basins. Type 1 piggyback basins display a high length:width ratio, if a sufficiently long thrust complex is incorporated. The Tannheim–Losenstein basin constitutes a long (> 400 km) and narrow (*c*. 30 km) deep-water trough in front of higher NCA thrust system (Fig. 4), bounded to the north by an actively deforming high of Austroalpine basement slices, together with ultrabasic bodies (Gaupp, 1983; Pober and Faupl, 1988). Rapid exhumation of the source area is indicated by the existence of a high-gradient, mountainous source area (von Eynatten and Gaupp, 1999) and fission track ages of about 120 Myr from detrital zircons of the Losenstein Fm (von Eynatten, 1996).

The northern source area is interpreted as a transpressive frontal part of the accretionary wedge, north of the NCA. This belt formed an emergent mountain range during most of the deposition of the Tannheim–Losenstein basin, based on the polymict clast compositions and rounding of pebbles. Consequently, the formation of this northern source, including ophiolitic material, sheds some light

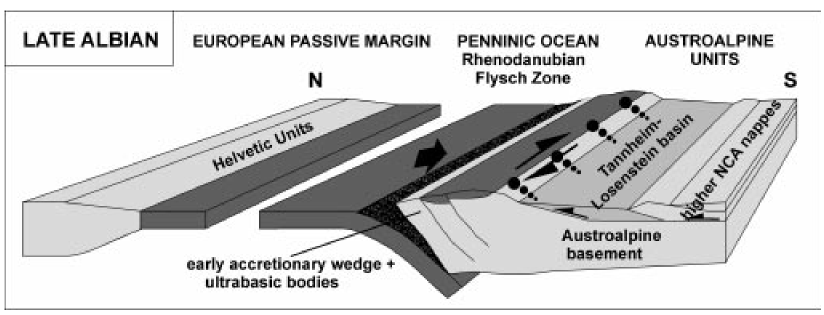

Fig. 4 Plate tectonic model for the middle/late Albian Austroalpine–Penninic plate boundary and the Tannheim–Losenstein basin. The basin formed as a piggyback trough in front of higher NCA nappes. The northern source area for the Tannheim–Losenstein basin is interpreted as an accretionary wedge as a consequence of oblique southward subduction of the Penninic oceanic plate.

on the Cretaceous evolution of the northern Austroalpine margin. Jurassic to Early Cretaceous northwards prograding thrusting from internal to external units of the NCA was interpreted to result from the closure and suturing of an oceanic basin located south of the NCA (e.g. Gawlick *et al.*, 1999). The area of the later Tannheim–Losenstein basin was characterized by quiet deposition of pelagic limestones during the Early Cretaceous. This passive margin setting changed to an active margin during the late Aptian/Albian, resulting in synorogenic basin formation (cf. Winkler, 1996; von Eynatten and Gaupp, 1999; May and Eisbacher, 1999). The rise of a northern, 'exotic' source area during late Aptian/early Albian times and related compression along the northern Austroalpine margin may be interpreted as a result of the onset of southward subduction of the Penninic ocean (Fig. 4). This is also supported by the onset of siliclastic flysch in the Rhenodanubian Flysch Zone to the north of the Austroalpine (Decker, 1990; Faupl and Wagreich, 2000). Thus, the Cretaceous piggyback basin formation and its siliciclastic filling from the north argues against a Turonian or later start of the Penninic subduction as suggested by Willingshofer *et al.* (1999).

Syndepositional northwestward thrusting of the southern, Lechtal–Reichraming–Lunz nappe system during the filling of the Tannheim–Losenstein basin is inferred from the shallowing upward trend with Albian neritic limestones at the northern margin of this nappe system. Some of the slumps rich in carbonate clasts in the upper part of the Losenstein Formation may have been derived from this southern thrust front overriding the basin, although the majority of the siliciclastic detritus derived from the north. The existence of blind thrusts below the basin can explain along-strike thickness variations. Sedimentation in the Tannheim–Losenstein basin ended simultaneously during the lowermost Cenomanian in the entire NCA (Weidich, 1990) and the CWC as a consequence of overthrusting.

Conclusions

The sedimentation of the Tannheim and Losenstein Formations during Aptian to early Cenomanian times indicates a special type of syntectonic basin within the Cretaceous orogenic wedge of the Eastern Alps.

1 The Tannheim–Losenstein basin is interpreted as an early, deep-marine piggyback trough in the footwall of thrusts. The basin was filled by a northerly derived coarsening-upward cycle, which indicates southward progradation of a coarse-grained slope apron. Clasts give evidence for a uniform source area to the north, comprising continental basement, Mesozoic sedimentary rocks and ophiolites.

2 The narrow basin extended over the entire length of the NCA (> 400 km) and continued into the Central Western Carpathians, where similar deposits, such as the Poruba Formation of the Križna Nappe, are known.

3 Subsidence and siliciclastic input into the basin marked the onset of compression in a transpressional continental margin setting during the late Aptian/Albian along the Austroalpine northern boundary.

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